Active Noise Control of Radiated Noise From Jets

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OUTLINE

I. Background/Motivation

II. Innovation

III. Impact of Innovation if Implemented

IV. Technical Approach

V. Phase I Results
   A. Experimental Set-Up
   B. Open Loop Acoustic Results
   C. Closed Loop Acoustic Results

VI. Dissemination Plan

VII. Future Work

BACKGROUND - JET NOISE

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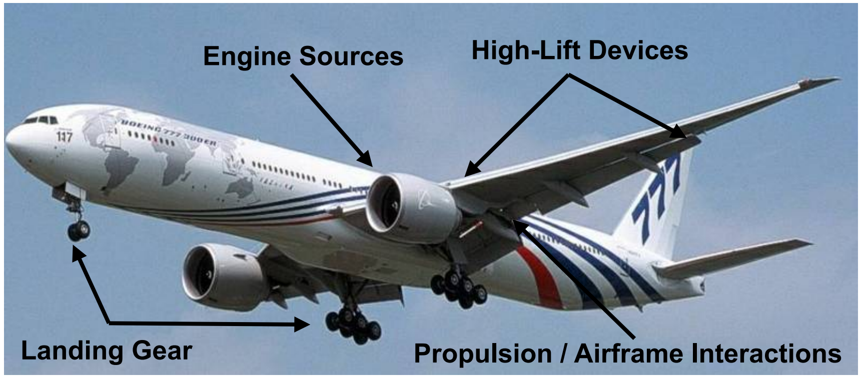
- Aircraft noise is considered to be **the most significant barrier** to increasing capacity of our national airspace system



- Jet noise is a dominant source of aircraft noise, particularly at takeoff

- Jet noise can adversely affect
  - Communities near airports
  - Passengers during cruise
  - Military support personnel supporting aircraft operations

* Dr. Joseph Doychak, Dept. of Navy Jet Noise Reduction Project Overview, Partners in Environmental Technology Technical Symposium and Workshop, Dec. 1, 2010

BACKGROUND – PROVEN REDUCTION

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- Two proven jet noise reduction methods flying commercially are:

- Increased bypass ratio (BPR)

- Increasing BPR changes the engine cycle, reducing jet velocities and hence noise
- Not as practical for military aircraft

- Chevrons at the nozzle exit

QTD2

Trent 1000 on Boeing 787

- Chevrons introduce streamwise vorticity
  - increases mixing
  - reduces jet potential core length
  - decreases low frequency noise

BACKGROUND – ACTIVE CONTROL

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- Active control of jet noise has traditionally followed two paths
    - Plasma actuation (Samimy *et al.* 2007, Brown 2008)
    - Fluidic injection (Krothapalli *et al.* 2002, review by Henderson 2010)
- Mechanical actuation of flaps or tabs, either piezoelectric or otherwise has also been investigated (Butler & Calkins 2003, Bauer, *et al.* 2012)
- Current active techniques rarely involve closed loop control
- Nonetheless, recent numerical studies by Babucke, *et al.* 2009 and Freund 2010 suggest optimal time-accurate perturbations would be required to significantly reduce jet noise

INNOVATION

- The use of an adaptive feedforward control configuration in conjunction with piezoelectrically-actuated vibrating chevrons

- Neither the adaptive feedforward control methodology nor the high-bandwidth vibrating chevron geometry has previously been explored in the context of jet noise reduction

- Existing active techniques
  - fluidic injection – significant mass flow requirements
  - plasma actuation - substantial power requirements

- Current approach explores enhancing noise reduction potential of passive chevrons with minimal power, weight using adaptive control

POTENTIAL IMPACT

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- Assuming closed-loop active chevron innovation is successfully demonstrated in more relevant environments and eventually implemented …

- Increased jet noise reduction at **takeoff** would facilitate
  - Containment of objectionable noise within airport boundaries
    - A strategic goal of Fixed Wing and High Speed Projects within Fundamental Aeronautics Program

From airliners.net photo by Mick Bajcar

- Increased jet noise reduction at **cruise** would facilitate
  - Potential for reduced fuel burn and emissions
    - Due to weight savings in reduced cabin sidewall treatment

POTENTIAL IMPACT

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- Reduced operational challenges for jet-powered Unmanned Aircraft Systems (UAS)

- Partnership with the Navy's jet noise reduction program
  - Veteran's Affairs now spends over $100 million annually* in hearing loss benefits to veterans often exposed to jet noise

* Dr. Joseph Doychak, Dept. of Navy Jet Noise Reduction Project Overview, Partners in Environmental Technology Technical Symposium and Workshop, Dec. 1, 2010

TECHNICAL APPROACH

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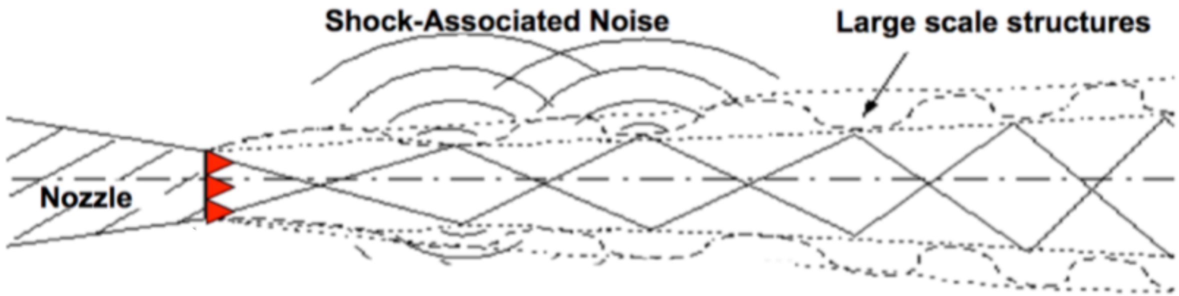

- Intention of the actuated chevron is to
  - Introduce additional energy at the chevron tip through small oscillations
  - Further encourage mixing within the jet shear layer
  - Inhibit growth of the large scale structures responsible for dominant low frequency jet mixing noise

- Furthermore, if the shock cell strength and/or spacing can be affected by the actuation, there is potential for broadband shock noise reduction

- Adaptive control of fluctuations should serve to enhance noise reduction potential

TECHNICAL APPROACH - ACTUATION

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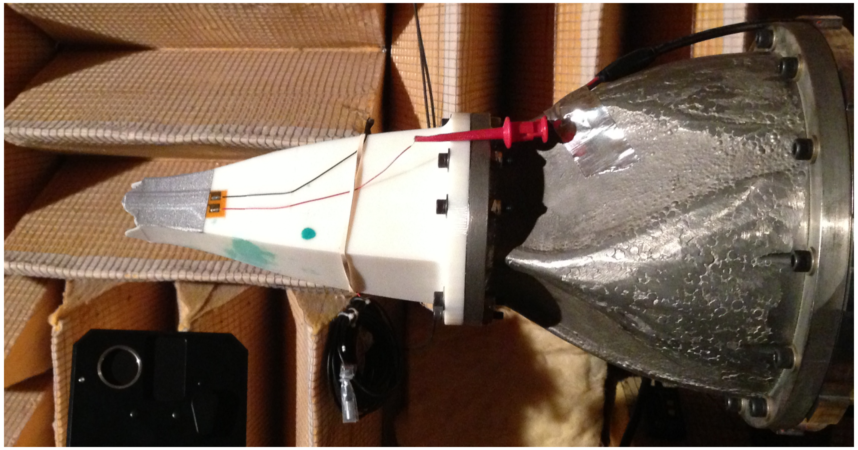
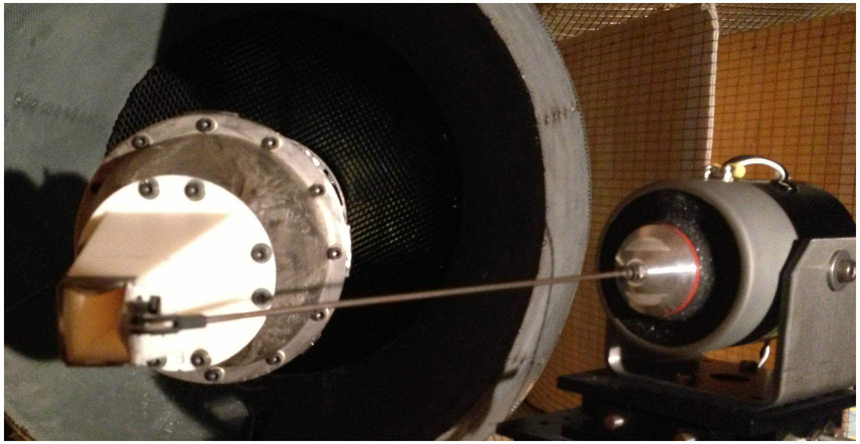
- Several chevron actuation schemes were considered and two were downselected for initial testing:

Macro Fiber Composite (MFC) Piezoelectric Patch Actuator



Mechanical shaker with nylon hinge and clevis attachment



- Shaker provided significantly more displacement
- However, frequency response and robustness issues led to the downselection of the piezoelectric patch as the primary actuation mechanism

TECHNICAL APPROACH - CONTROL

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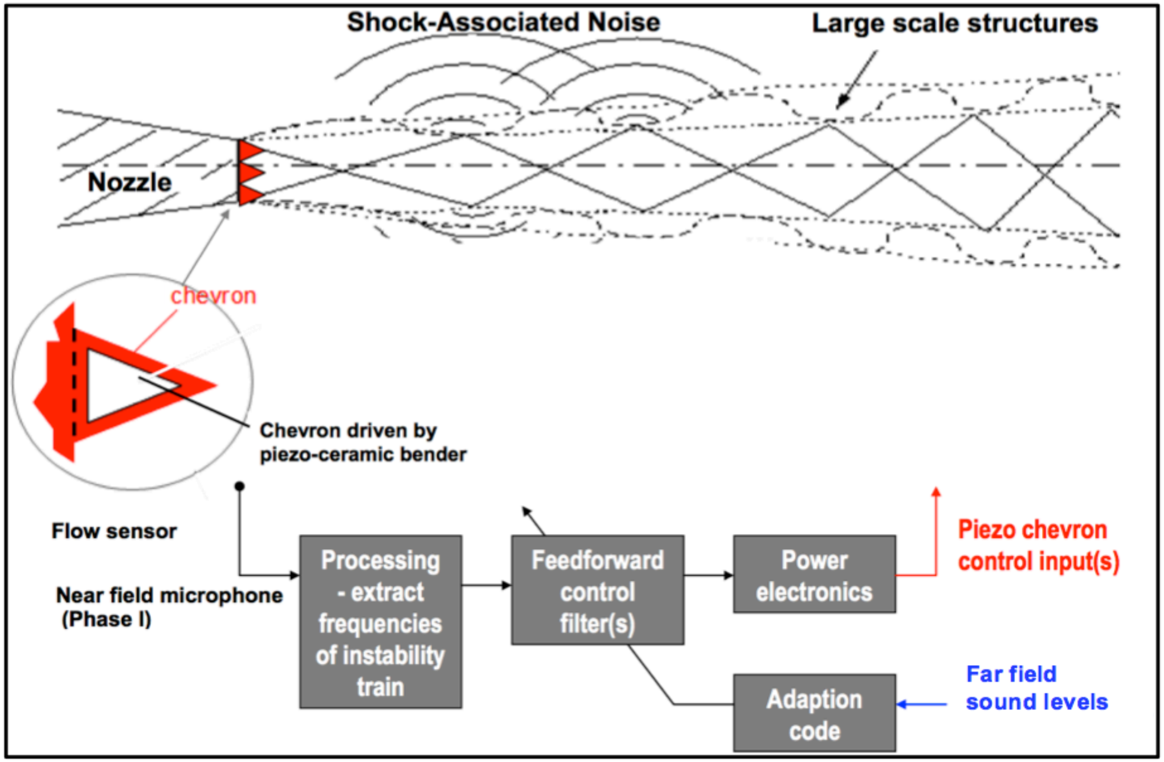
- Feedforward control strategy
  - Provides opportunity for adaptive control and avoids stability issues of some feedback systems
  - Most effective when reference sensor provides information prior to the control (not possible in this case)
  - For proof-of-concept, a bandpass filter was applied to broadband signal, typically at natural frequency of chevron



OBJECTIVE

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- Demonstrate the potential for the closed-loop active noise control of high-bandwidth active chevrons to reduce jet noise

  - Focus on demonstration of feedforward strategy for Phase I
  - Focus on demonstrating actuation of a single chevron
  - Focus on a functioning system that has potential for noise reduction beyond a static chevron case
  - Consider potential for both jet mixing noise reduction and broadband shock noise reduction

EXPERIMENTAL SET-UP

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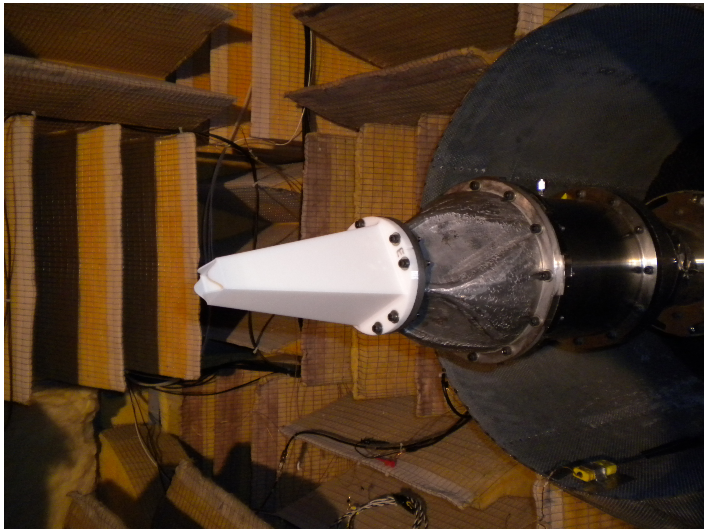
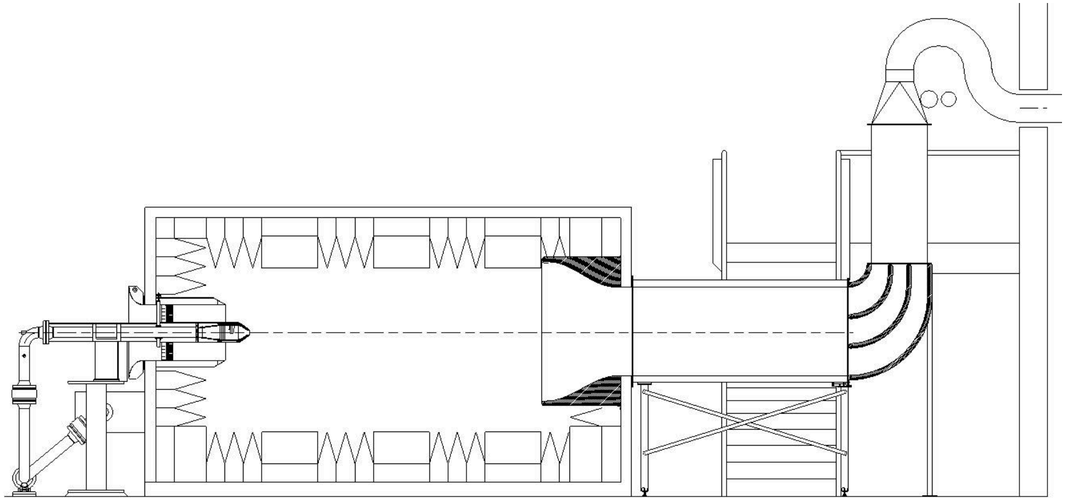
Small Anechoic Jet Facility (SAJF)

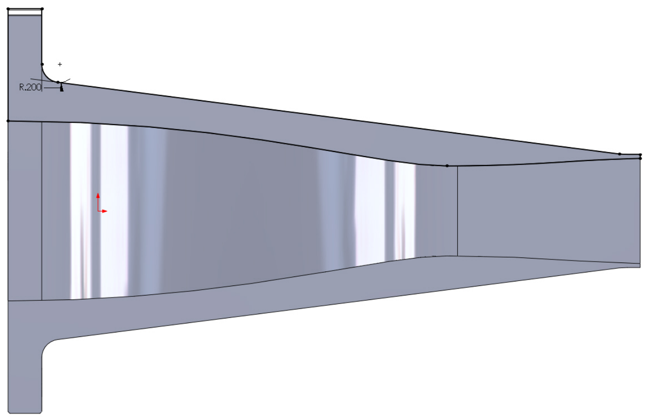


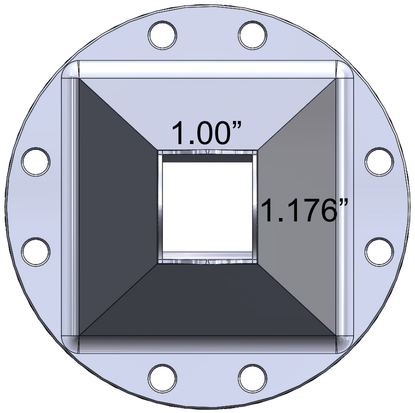


- Capable of 2 lbm/s single stream flow, nozzle pressure ratio up to 8
- 275 kW electric heater provides heated jet capability
- 2 ft diameter coflow duct capable of minimal velocity with single speed exhaust fan
- Anechoic chamber 12.67 ft length x 8.38 ft width x 10.7 ft height to wedge tips, providing anechoic environment down to 250 Hz
- 6" diameter axisymmetric to 2" square transition piece used to mate to nozzles

3-D PRINTED NOZZLES

- Converging-diverging rectangular nozzles made from ABS plastic using 3-D printer

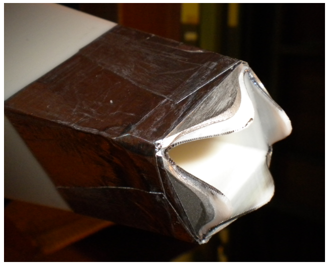




- Contoured designed using Method of Characteristics for $M_d = 1.5$
- Two parallel walls, two diverging walls

- Nozzle exit 1.0”× 1.176”
- D_{eq} = 1.224”
- Throat 1” square

- Manufacturing efficient and cost effective, however, cracking near chevron roots became apparent, requiring non-excited chevrons to be reinforced with metal plates



CHEVRON DESIGN

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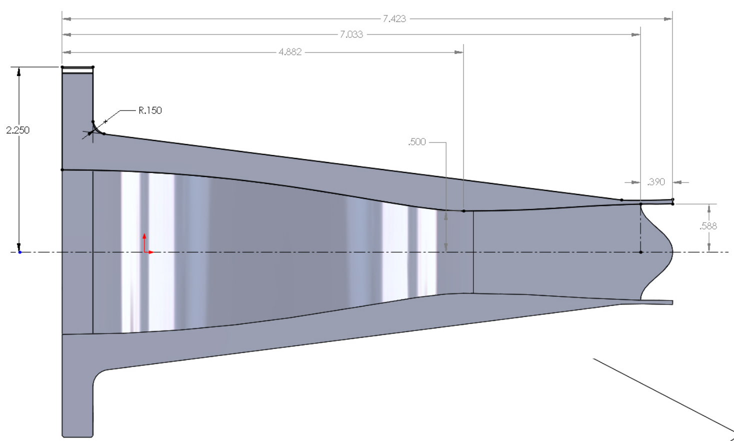
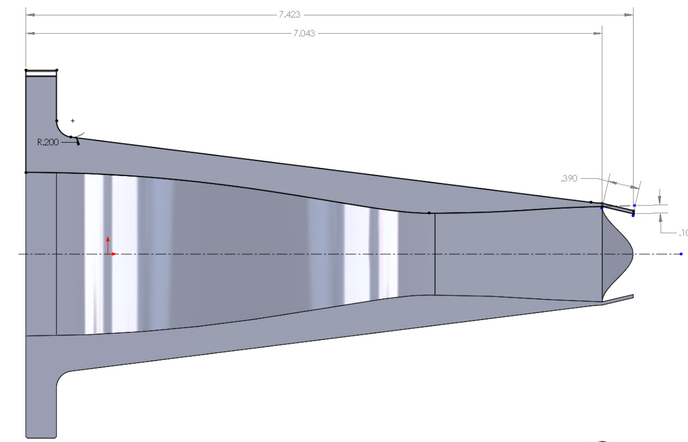
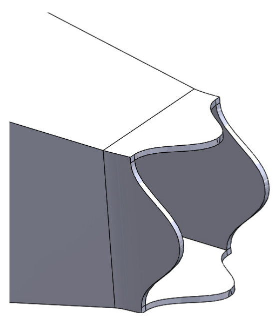
- Chevron design scaled from previous work with Boeing on Hybrid Wing Body chevron nozzle set
  - Width = to full sidewall dimension, (1.0”, 1.176”)
  - Length = 0.393”
  - Varying penetration

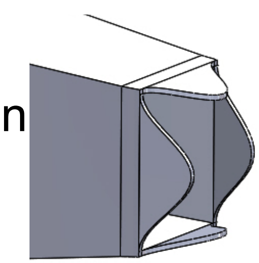




Originally chevrons followed diverging contour but were not effective



Converging chevrons with varying levels of penetration were considered



STRUCTURAL CHARACTERIZATION

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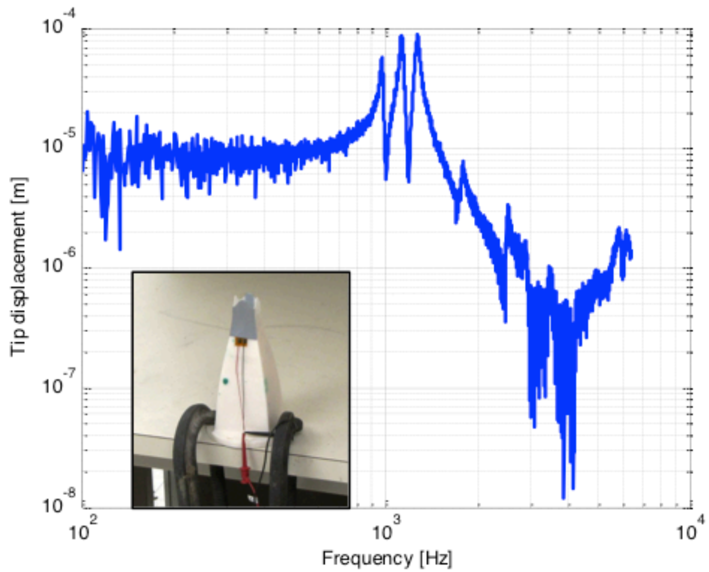
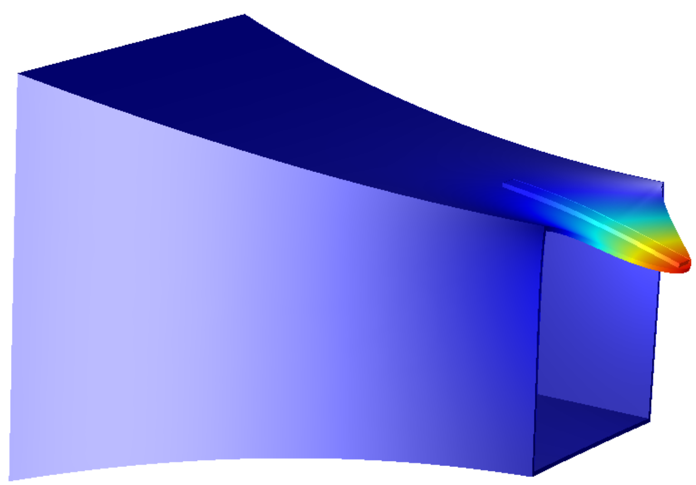
- MFC actuator selected for benchtop tests and bonded to outer surface of chevron with strain gauge adhesive
- Reflective tape placed over actuator for laser vibrometer measurements



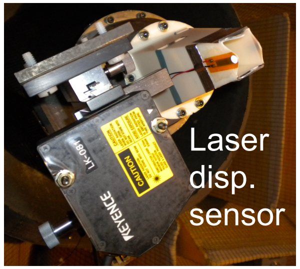
Maximum tip displacement of ~ 0.1 mm at nozzle resonant frequency near 1000 Hz



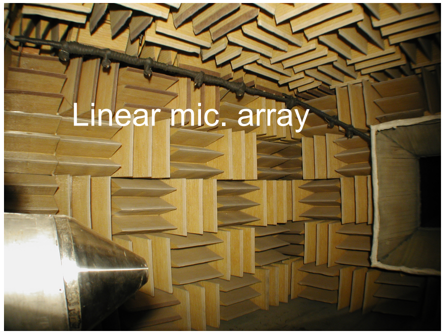
Simulated mode shape at 906 Hz using COMSOL

INSTRUMENTATION AND FLOW CONDITIONS

- Chevron tip displacement measurements using accelerometer for initial characterization, then laser vibrometer or laser displacement sensor



- Far-field acoustic results from 8-microphone linear array, data includes
  - Microphone diffraction and actuator corrections
  - Atmospheric attenuation to lossless conditions
  - Spectral data bin width 25.63 Hz
  - Data propagated to 1 ft arc



Flow Conditions Investigated

NPR	*M*	T_T (°R)	$f_c = U_j/D_j$ (Hz)
1.064	0.3	560	3,370
1.692	0.9	560	9,497
2.77	1.3	560	12,778
3.182	1.4	560	13,493
3.67	1.5	560	14,164
4.25	1.6	560	14,796

CHEVRON PENETRATION STUDY

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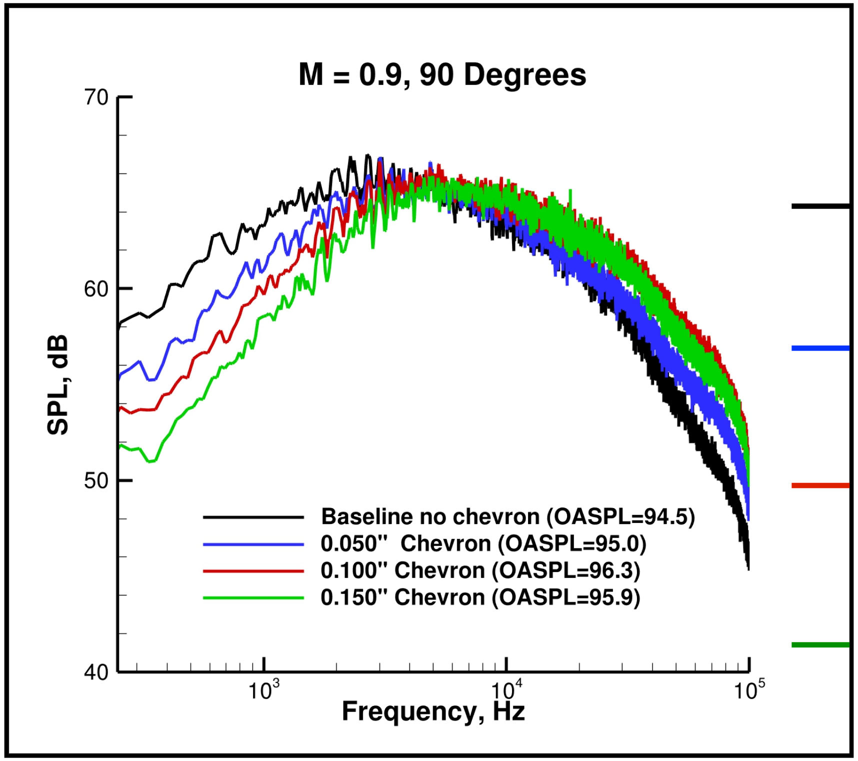

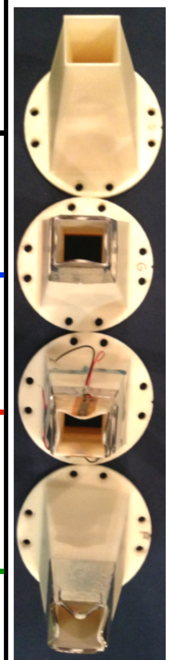

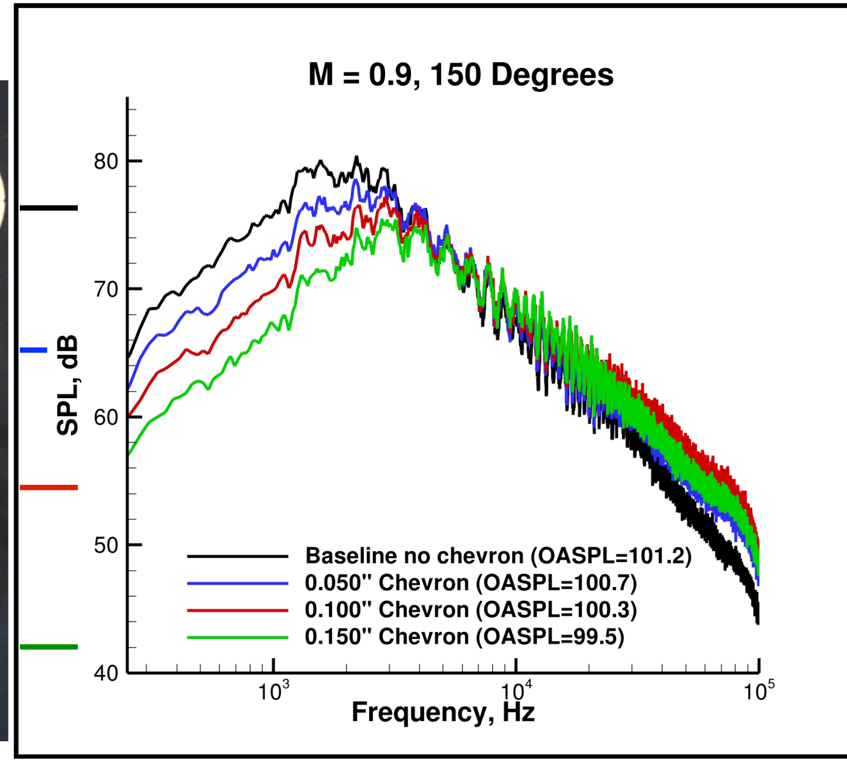

- Expected low frequency benefit and high frequency penalty seen with increasing chevron static penetration (radial dist. from chevron tip to diverging nozzle contour)
- The 0.100” static penetration nozzle was further investigated but 0.150” shows promise due to further low frequency benefit but comparable high frequency penalty

OPEN LOOP RESULTS

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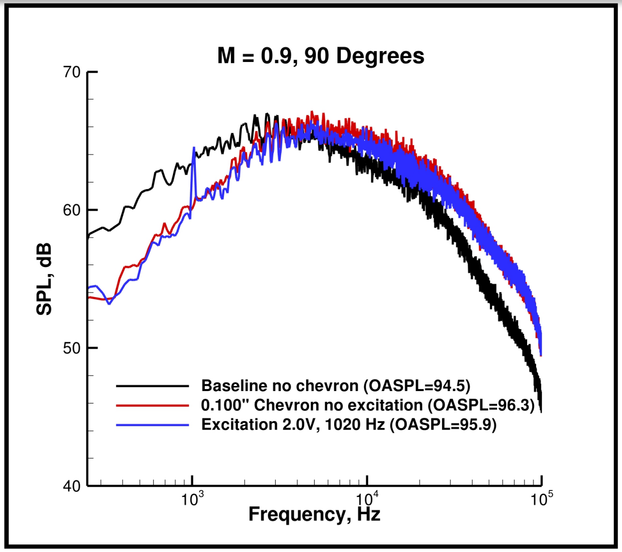
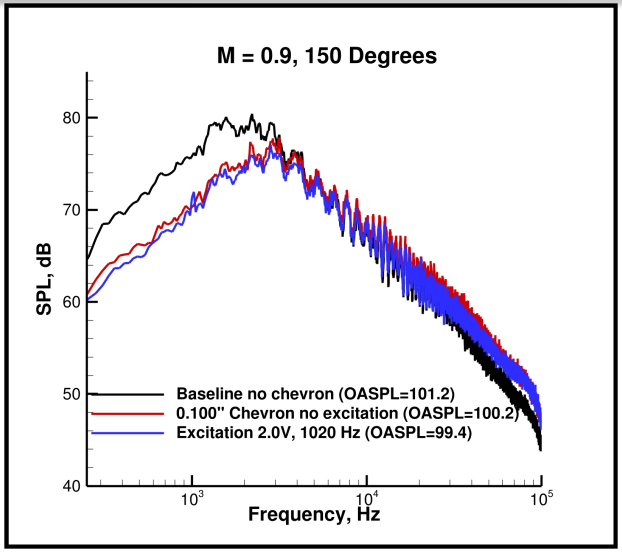
M = 0.9

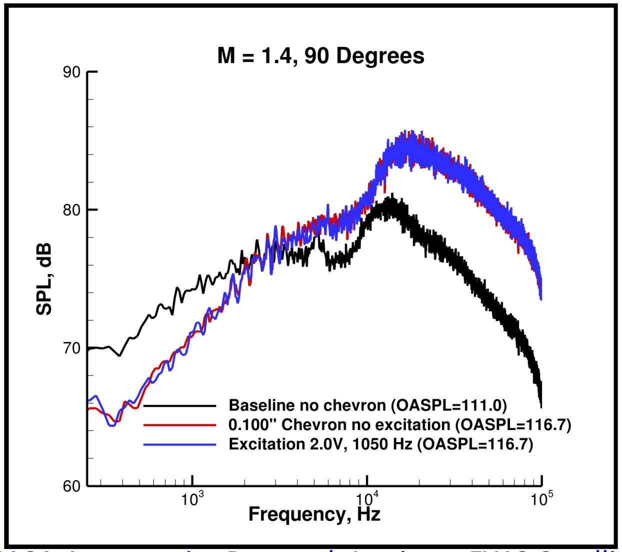
- Excitation reduces chevron penalty at high frequencies and increases chevron benefit at low frequencies

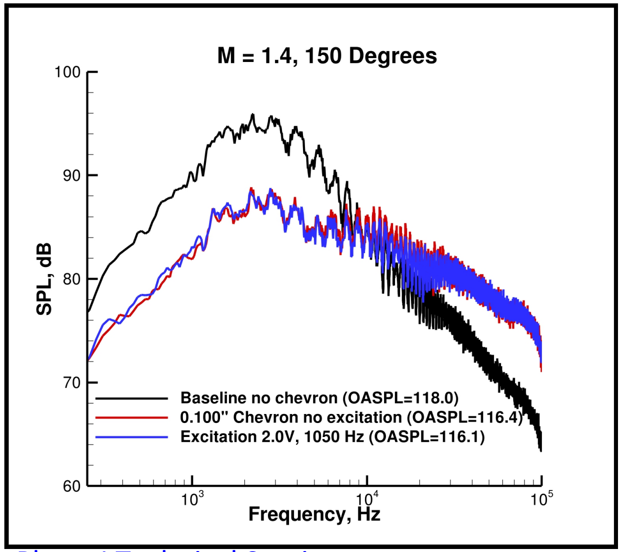




M = 1.4

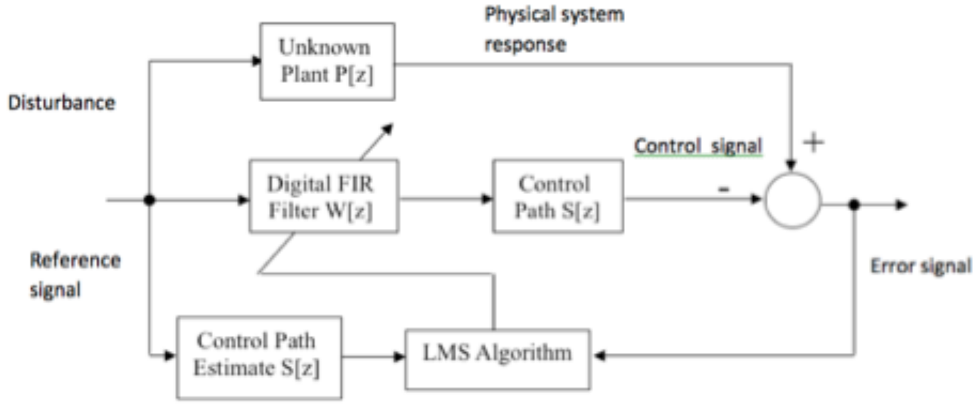
- Excitation does not alter broadband shock associated noise penalty





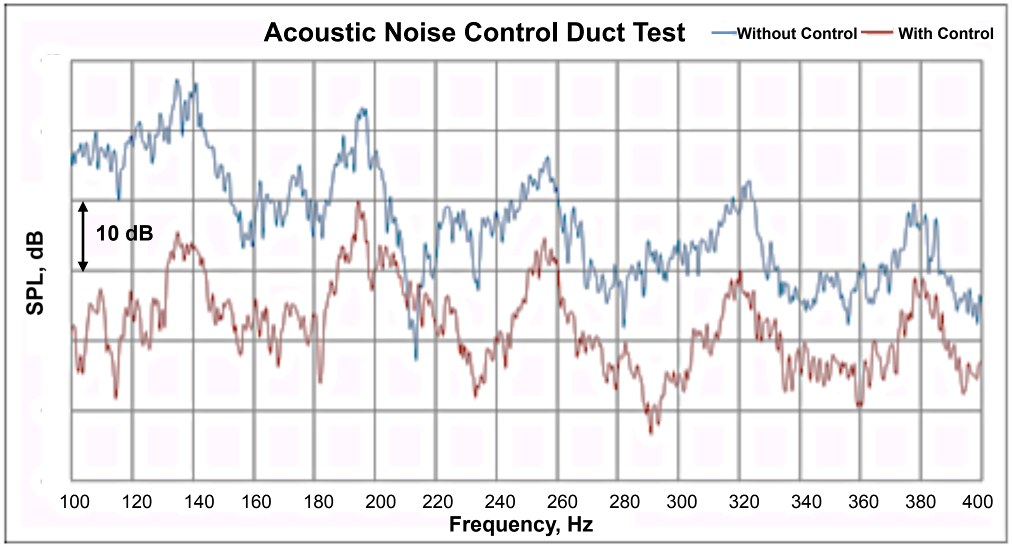
CLOSED LOOP CONTROL

- Digital feedforward control approach utilizes filtered-reference least mean square (FXLMS) algorithm



- Benchtop experiment involved long tube with speaker driven by white noise at one end

- Drive signal to speaker also served as reference to controller



- Active sound speaker near duct outlet was driven by controller

- Controller provides significant reduction across broad frequency range

CLOSED LOOP CONTROL

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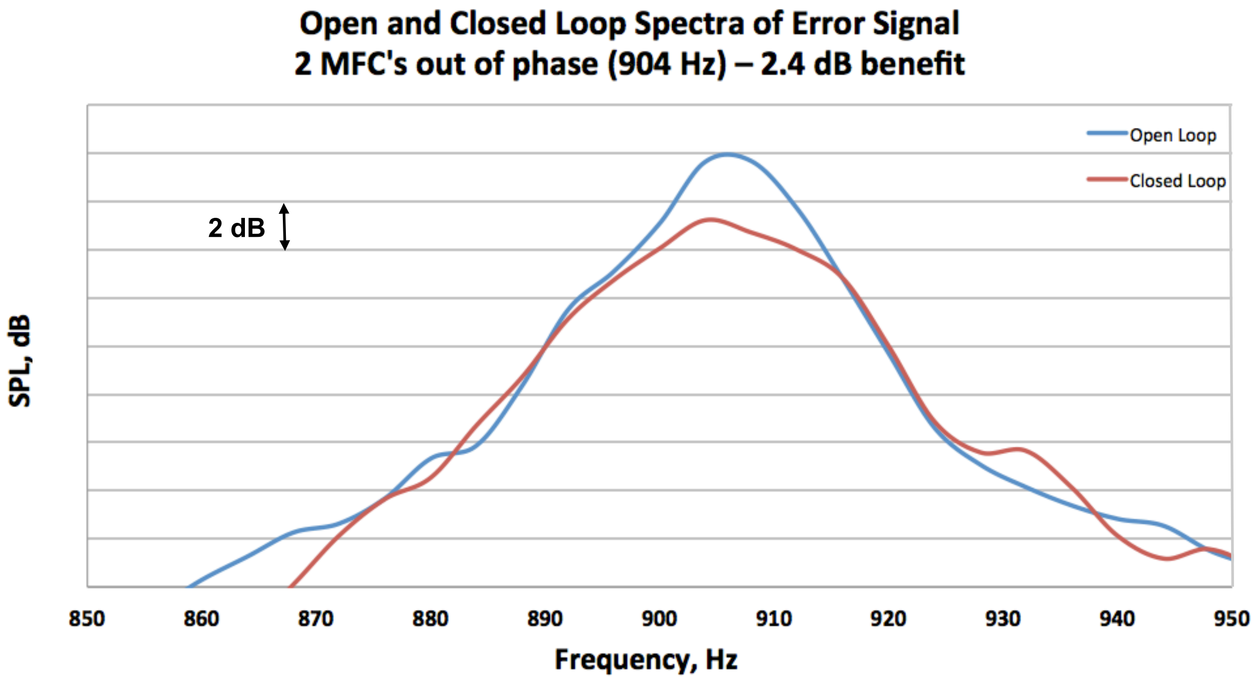
- Implementation into SAJF used a near/mid field microphone as reference sensor and additional far field microphone near 155° as error sensor
- Recall since reference sensor cannot provide information prior to control in this case, a bandpass filter was applied
- Closed loop benefits at single bandpass frequency are routinely 1-3 dB



CLOSED LOOP RESULTS

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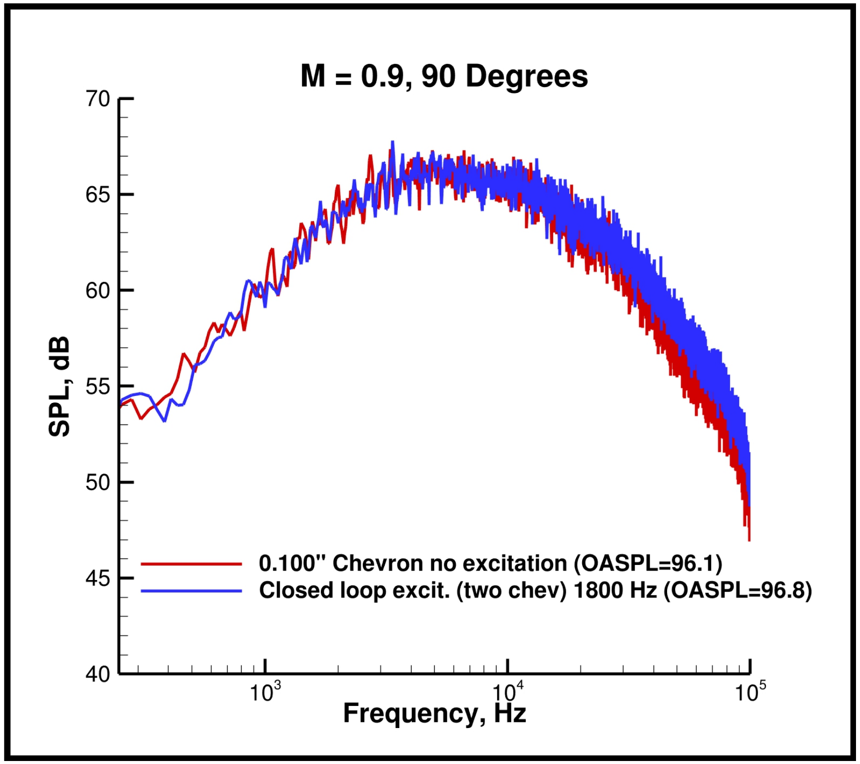

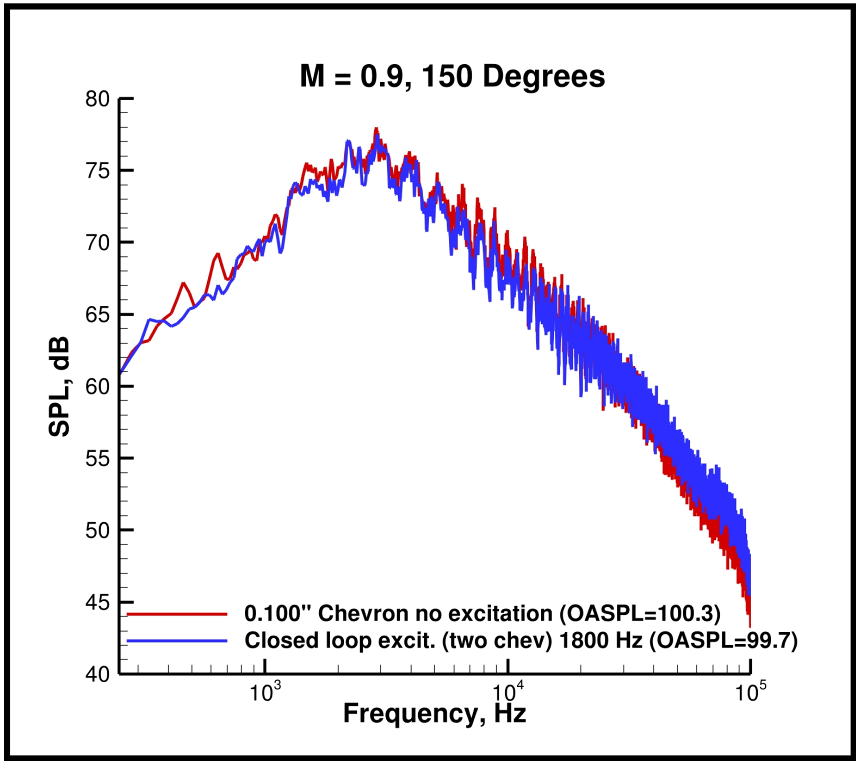

- Excitation with closed loop control showed overall penalty at 90°, overall benefit at 150° that is comparable to open loop overall benefit
- Reductions most apparent at low frequencies
- Attenuation likely to improve with increased number of active chevrons

SUMMARY

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- The use of an adaptive feedforward control configuration in conjunction with piezoelectrically-actuated vibrating chevrons is an innovative method for jet noise reduction

- A Macro Fiber Composite (MFC) patch actuator configuration was downselected for its frequency response and integrated with ABS supersonic rectangular nozzle

- Acoustic investigation of static chevron penetration led to nozzle with static penetration of 0.100”

- Open loop excitation investigations of this arrangement showed
  - Increased chevron benefits by up to 0.8 dB OASPL relative to the same chevron geometry without excitation
  - Decreased chevron penalty at high frequencies
  - Minimal impact on broadband shock associated noise

SUMMARY

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- Digital feedforward algorithm demonstrated effectiveness in benchtop test using speaker tube sound source

- Installed closed loop actuation system in SAJF showed reductions at select frequencies of 1-3 dB

- Integrated spectral levels showed benefits compared to the static chevron case at aft angles but no significant broadband reduction beyond the open loop benefits, likely due to controller design for narrowband performance

DISTRIBUTION / DISSEMINATION

- As relevant results have become available, discussions have taken place with NASA Project personnel and industry
  - Russ Thomas (ERA Project Engineer for Vehicle Systems Integration Subproject)
  - James Bridges (High Speed Project Tech Lead for Airport Noise Technical Challenge)
  - Tad Calkins (Associate Technical Fellow, Boeing Research and Technology)

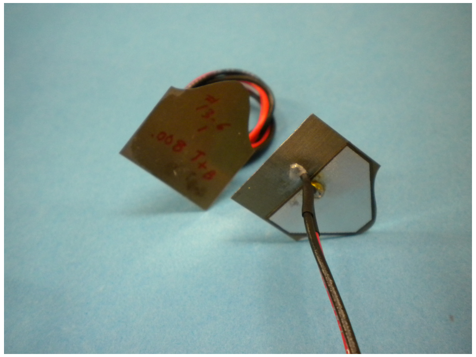
- Discussions with Boeing led to investigating a way to partner, including teaming on the Phase II proposal

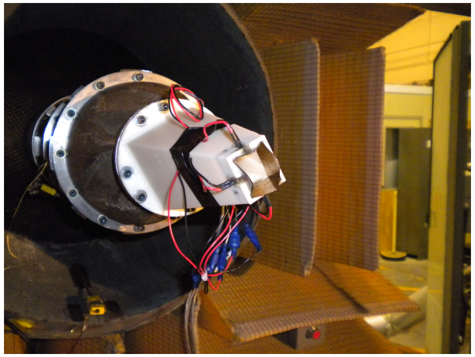
- In addition to current presentation, formal presentation to wider technical community would occur either at
  - Fall Acoustics Technical Working Group Meeting, Hampton, VA, October 2013

    or
  - 2014 Aeroacoustics Conference, Atlanta, Georgia, June 2014

NEXT STEPS

- Currently investigating the use of pre-stressed piezo-ceramic actuators
  - Order of magnitude increase in displacement authority over conventional MFC actuators
  - Stainless steel substrate is custom designed to incorporate entire chevron geometry
  - Potential actuation of all four chevrons





- Initial test runs suggest penetration depth will need to be increased
  - Inherent curvature essentially taken out through bonding process

NEXT STEPS

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- Phase II Proposal with Boeing expertise would focus on enhancing jet noise reduction potential of Active Noise Control (ANC) system by
  - Optimizing the actuator configuration with pre-stressed piezo ceramic actuators
  - Expanding the control strategy beyond select frequency demonstration using
    - Simple feedback control
    - Multiple Input Multiple Output (MIMO) feedforward control
    - Internal Model Control (IMC)
    - Generalized Predictive Control (GPC)
  - Increasing understanding of the effects of actuation on flowfield by measuring the mean and turbulent flowfields with PIV
  - Using more relevant nozzle geometries (faceted axisymmetric metal nozzle) with full actuation of increased number of chevrons including phasing
- Furthermore, a larger scale test is proposed in the Low Speed Aeroacoustic Wind Tunnel (LSAWT) to
  - Achieve more realistic scale between chevron size and nozzle diameter
  - Account for the effects of the flight stream on the reduction capability

BACK-UP SLIDES

REPEATABILITY

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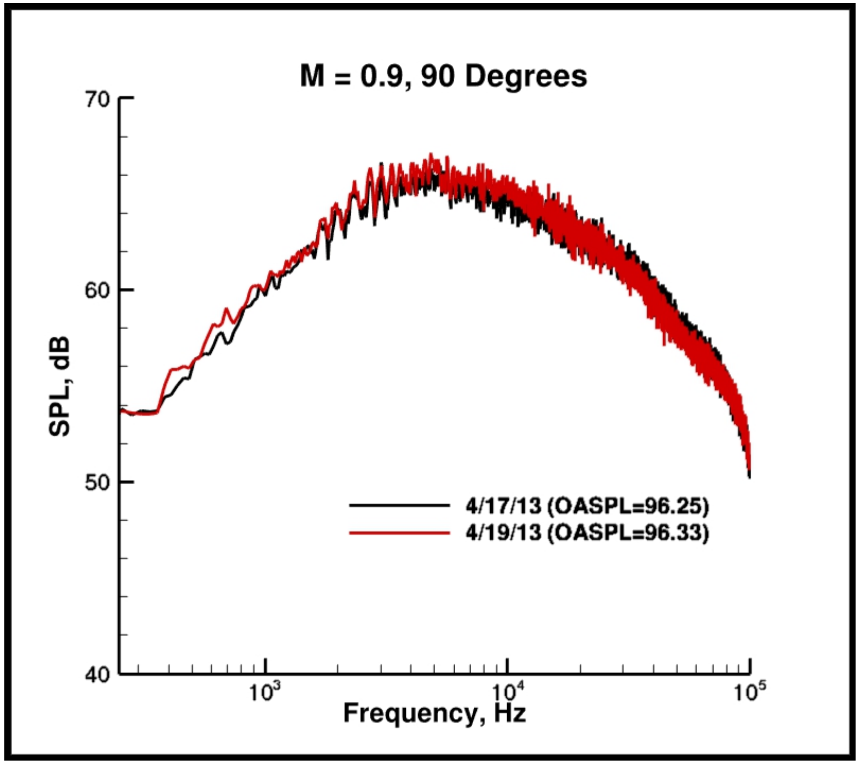

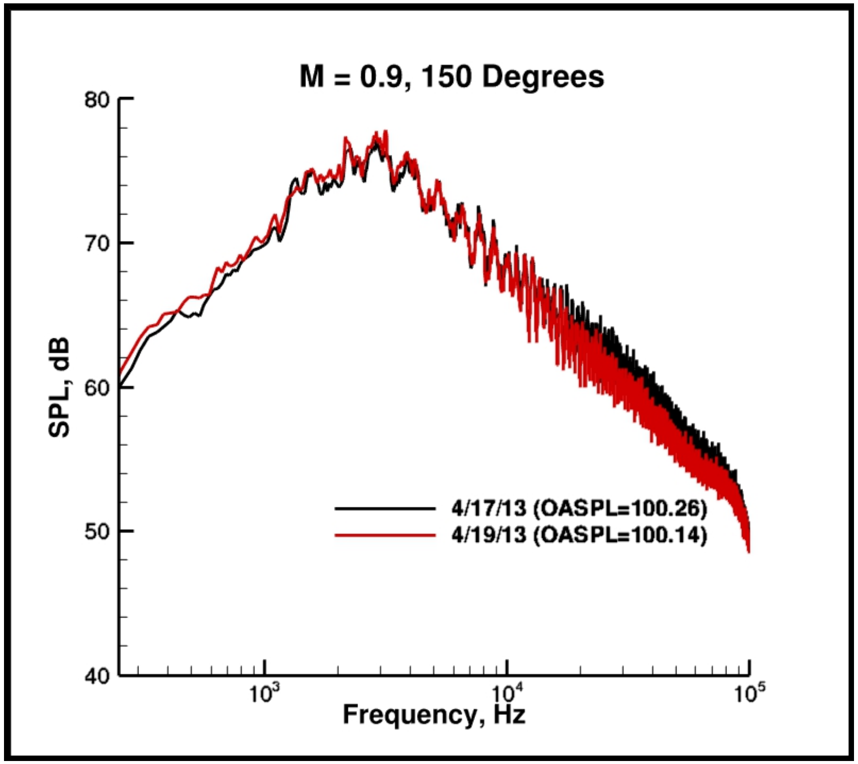

- Comparisons are typically made for same-day data to minimize day-to-day uncertainty
- However, day-to-day comparisons within 0.12 OASPL

CONTROL ALGORITHMS

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- Simple Feedback Control
  - Artificially generated control signal thus uncorrelated with flowfield and noise of jet near the nozzle
  - Different forms of control signal to be investigated (multiple narrowband, random noise, etc.)
- MIMO Feedforward Control
  - Utilizes independent but coupled control signals driving multiple actuators
  - Expect better control authority than with current single channel feedforward method
- Internal Model Control
  - Requires no reference sensor and utilizes model of internal dynamics of plant to modify feedback arrangement and convert it to feedforward
  - Digital adaptive filters can then be utilized similar to current approach
- Generalized Predictive Control
  - Optimal feedback control strategy
  - Enables an adaptive implementation